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PERFORMANCE OF CENTERBODY VORTEX GENERATORS IN AN AXISYMMETRIC MIXED-COMPRESSION INLET AT MACH NUMBERS FROM 2.0 TO 3.0

by Glenn A. Mitchell and Ronald W. Davis

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ABSTRACT

Three vortex-generator configurations were installed aft of the inlet throat on the centerbody of a Mach 3.0 mixed-compression inlet. The three were about equal in improving diffuser pressure recovery and all produced significant, although unequal, reductions in distortion. Only the most densely spaced configuration generated vortices that dissipated before reaching the compressor face. Vortex generators effectively energized the normally retarded flow adjacent to the centerbody even during supercritical operation where they were immersed in supersonic flow. Generators were also effective at inlet angles of attack to at least 5°.

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SUMMARY

Vortex generators were installed immediately downstream of the throat on the centerbody of a Mach 3.0, axisymmetric, mixed-compression inlet. The ability of three different vortex-generator configurations to increase diffuser pressure recovery, reduce distortion, and inject high-energy air into the normally retarded flow region adjacent to the centerbody was evaluated at Mach numbers from 2.0 to 3.0.

The three vortex-generator configurations were about equal in improving diffuser pressure recovery. All generator configurations produced significant, although unequal, reductions in distortion. Only the most densely spaced configuration generated vortices that dissipated before reaching the compressor face. Vortex generators were effective in energizing the retarded flow region, even during supercritical operating conditions where they were immersed in supersonic flow. Generators were also effective at inlet angles of attack to at least 5°.

INTRODUCTION

Inlets of short length with a high rate of subsonic diffusion are generally afflicted with relatively large values of total pressure distortion at the engine face. Boundary-layer bleed can be used to reduce distortion (ref. 1) but not without added ducting weight and bleed drag penalties. Vortex generators are an alternate boundary-layer control device without such penalties. The ability of vortex generators to mix high-energy air into the low-energy boundary layer has been reported in references 2 to 5. Increased diffuser performance resulting from the use of vortex generators was reported in references 5 to 9. The present investigation was conducted to determine the effectiveness of several vortex-generator configurations installed on the centerbody of a Mach 3.0, axisymmetric, mixed-compression inlet. The vortex-generator performance was investigated in the Lewis 10- by 10-foot supersonic wind tunnel at Mach numbers from 2.0 to 3.0 and at angles of attack to 5°. The effect of various internal flow fields produced by inlet supercritical operation and off-design spike position were investigated at the design Mach number.

SYMBOLS

A	area, sq cm
A_l	projected inlet area, 1660.4 sq cm
A_3	diffuser-exit area, 890.4 sq cm
D	diameter, cm
h	vortex-generator height, 0.89 cm
L	length, cm
M	Mach number
P	total pressure, N/m^2
p	static pressure, N/m^2
r	radius, cm
S	spacing between sets of divergent vortex-generator pairs, cm
s	spacing between airfoils of a converging or diverging vortex-generator pair, cm
x	linear distance, cm
Δx	spike translation from design position, positive when spike is extended, cm

Subscripts:

con	converging vortex generators
crit	critical conditions
d	subsonic diffuser
div	diverging vortex generators
i	inner third of diffuser flow area at compressor face station
l	cowl lip station
max	maximum

min minimum

x conditions at x-distance

0 free-stream station

3 diffuser exit station

Superscript:

—— average

APPARATUS AND PROCEDURE

Inlet Model

The inlet (fig. 1) was designed to have a 1-percent total pressure loss through the initial shock at the design Mach number of 3.0. Isentropic focused compression reduced the Mach number to an average of 2.37 at the cowl lip station (fig. 2). The internal cowl surface then turned the flow back toward the model centerline in two steps of approximately 12° each. The resulting oblique shocks were focused on the model centerbody which was turned at the focal point to align the surface with the flow direction and prevent shock reflection. A centerbody bleed slot was located just forward of the shock location to remove the spike boundary layer. The supersonic diffusion reduced the Mach number to an average of 1.45 at the inlet throat. The initial part of the subsonic diffuser was provided with two hydraulic diameters of essentially constant area and was followed by an equivalent 12° conical area expansion to the simulated compressor face approximately 1.5 inlet diameters from the cowl lip.

The inlet had a translating spike which retracted to position the cone shock on the cowl lip at the inlet design Mach number of 3.0 and extended to reduce the contraction ratio to that necessary to start the inlet or for operation at lower Mach numbers. Figure 3 presents the diffuser internal area variations for spike positions $(\Delta x/D_l)$ of 0, 0.064, and 0.138 which correspond to the highest contraction ratios allowing inlet operation at Mach numbers of 3.0, 2.5, and 2.0, respectively. Additional design details of this inlet can be found in reference 1.

Instrumentation

Total pressure recovery and distortion were measured by six radial rakes located at the simulated compressor face. A schematic diagram of the compressor face station (fig. 4) shows that the duct was divided into two halves by vertical struts which were necessary in order to discharge the centerbody bleed flow overboard. The circumferential positions of the rakes were not adjusted for these struts but were equally spaced at intervals of 60° around the duct. Each of the rakes contained six area-weighted total pressure probes, and a simple average of all probes was used to obtain total pressure recovery. Static pressure levels at the rake station were recorded by four equally spaced taps around the duct outer wall. Internal duct pressure distributions were obtained from a longitudinal row of internal cowl static pressure taps.

Vortex Generators

The cross section of each vortex generator was one-half of an NACA 0012 airfoil as shown in figure 5. An aspect ratio of 0.5 was selected from experimental data of reference 5. The height or span of the airfoil was 0.89 centimeter or about one-fourth of the inlet throat height. The chord was 1.78 centimeters. The leading edge of the airfoil was blunted as shown in figure 5 with a circle of radius of 0.018 centimeter.

The generators were installed on the model centerbody aft of the inlet throat. A photograph of the installed generators is shown in figure 6. Generators were not installed on the cowl side of the duct because previously unpublished data on this inlet had revealed that most of the low-energy flow was near the centerbody. Allowing for the total frontal area blockage of all the installed generators, the minimum flow area at the selected generator location was 2 percent greater than the throat area. The small area decrement of the generators is illustrated in figure 3.

Three different configurations of vortex generators were tested. These are illustrated in the photographs of figure 7 and sketched in figure 8. All of the spacings shown in figure 8 were measured from the generator mid chord. For each configuration, the generators were arranged in diverging pairs with each generator set at 16° angle of attack and the flat surface facing upstream. The initial vortex-generator configuration (configuration 1) was an equally spaced, counter-rotating system having 18 pairs of airfoils with a spacing to height ratio s/h of 3.5. The counter-rotating vortices thus produced are indicated by the arrows in figure 6. The design of configuration 1 was generally consistent with the design of the best-performing, counter-rotating generator designs reported in references 2 to 9.

Theoretical considerations (refs. 10 and 11) have indicated that increasing the spacing between sets of divergent generator pairs (S in fig. 8) relative to the spacing between individual airfoils of a divergent pair (s_{div} in fig. 8) would result in a strong induced velocity of the vortices toward the surface, presuming the ratio S/h is kept constant. This increase in vortex effectiveness would also be accompanied by a delay in the movement of the vortex away from the surface thereby increasing the downstream distance or range of effectiveness. The ratio S/s_{div}, which was equal to two for configuration 1, was therefore increased to three for configuration 2 (see fig. 8). The spacing of the individual airfoils of a divergent pair s_{div}/h was maintained at a value of 3.5. The spacing of airfoils of a convergent pair s_{con}/h was increased to seven. This arrangement also increased S/h which alone would tend to reduce the velocity component toward the surface but would also tend to increase the range of effectiveness. By combining the effects of the changes in S/s_{div} and S/h, configuration 2 would theoretically have increased effectiveness and also an increased range over configuration 1. Tending to counter these trends, however, was the fact that these changes reduced from 18 to 12 the total number of generator pairs which could be placed on the inlet centerbody.

Configuration 3 was an equally spaced, counter-rotating system with only nine pairs of generators, or half the amount of configuration 1. The ratio S/s_{div} was again two, but s_{div}/h and S/h were both double that of configuration 1. Theoretically, configuration 3 would tend to produce a smaller velocity component toward the surface than configuration 1 (reducing the effectiveness) but would have a longer range of effectiveness.

Because of the nonuniformity of the flow field aft of a vortex-generator system, the orientation of the total pressure rakes relative to the vortex generators could affect interpretation of the data if the vortex patterns persisted back to the rake station. The various vortex-generator configurations were positioned such that the generator-to-rake orientation was not consistent from configuration to configuration (see fig. 8). For configuration 1, the radial rakes were located directly aft of converging generator pairs. The rakes were aft of diverging generator pairs for configuration 2. In configuration 3, the rakes alternated between positions aft of converging and diverging pairs. To help determine the effect of orientation, a limited amount of data was obtained with configuration 1 indexed such that the rakes were positioned aft of diverging rather than converging pairs of generators. This is designated configuration 1A.

The investigation was conducted in the Lewis 10- by 10-foot supersonic wind tunnel over a Mach number range from 2.0 to 3.0 and at angles of attack to 5°. In addition, the effects of inlet supercritical operation and off-design spike position on vortex-generator performance were investigated at the inlet-design Mach number. Reynolds number was 3.75 million, based on the inlet diameter.

RESULTS AND DISCUSSION

Critical Performance

The inlet critical performance over the Mach number range is summarized in figure 9 for various angles of attack. As indicated by the compressor face static pressures presented in figure 9, all of the vortex-generator configurations obtained considerable improvement in diffuser efficiency relative to the clean configuration without generators. Static pressures were improved as much as 7 percent by the use of generators although the average improvement was around 3 percent. Differences between the static pressure levels obtained with the various vortex-generator configurations were generally small (around 1 percent) and varied with test conditions. Configuration 2 obtained the highest static pressure levels at 0^o angle of attack (fig. 9(a)). Configuration 1 appeared best at 2^o angle of attack at the higher test Mach numbers (fig. 9(b)). There was no significant difference in static pressures among the generator configurations at 5^o angle of attack (fig. 9(c)).

The total pressure recovery was also increased about 2 percent by vortex generators. The similarity in trends of the total pressure curves of figure 9 to the corresponding static pressure curves suggests that the total pressures were also indicating an increase in diffuser performance rather than an effect of rake orientation in a nonuniform flow field. In many instances, small differences in the static pressure levels of the various generator configurations were also apparent in the total pressure measurements. For example, at 0^o angle of attack (fig. 9(a)), where the static pressures were highest for configuration 2, the total pressures were also highest. Similarly, at 2^o angle of attack at the higher Mach numbers, the highest static and total pressures were obtained by configuration 1.

Although an average of the area-weighted compressor face total pressures is an acceptable method of obtaining diffuser pressure recovery, a true mass-weighted average is not obtained under conditions of considerable distortion. Therefore, the mass flow control plug settings used for each configuration were examined for confirmation of the increased pressure recovery indicated by the total pressure rakes. With the inlet at critical conditions, a decrease in the choked area at the plug, as reflected simply by plug position, would indicate increased total pressure recovery. (Critical is defined as the operating point with the terminal shock at the inlet throat and was easily found with this inlet as the last operating point preceding unstart.) Data was compiled in this manner at 0^o angle of attack and confirmed the higher rake total pressure recovery with vortex generators in the inlet. However, the plug settings indicated a total pressure recovery increase of only 1 percent was obtained with vortex generators. The plug data agreed with the pressure data in indicating that configuration 2 obtained the best diffusion at 0^o.

The parameter "inner-duct relative recovery" is presented in figure 9 and is defined as the pressure recovery of the inner one-third of the compressor face referenced to the complete duct average pressure recovery; or $(\overline{P}_i - \overline{P}_3)/P_0$. This parameter was adopted to directly measure the effectiveness of the various vortex-generator configurations in obtaining high-energy flow in the normally low-recovery region near the centerbody wall. Negative values of inner-duct relative recovery would indicate pressures near the inner wall to be below the average; and values near -0.10 would indicate separated flow near the duct hub. Conversely, positive values would indicate higher recovery near the hub than in the rest of the duct. As indicated by the inner-duct relative recoveries in figure 9, the low-energy air near the inner-duct wall was replaced with much higher energy air by all of the vortex-generator configurations. The inner-duct recovery was improved as much as 0.10 by the generators. Differences among the generator configurations in energizing the low-recovery region were small. Inner-duct recoveries varied less than 0.02. Within this range, however, configuration 1 was generally the most effective.

The inlet compressor-face distortion levels obtained for the various configurations were quite different. The clean configuration had quite high distortion levels (fig. 9). Distortions were 21 to 26 percent at 0° angle of attack over the Mach number range (fig. 9(a)). These levels were reduced by the use of vortex generators. Configuration 1 obtained the lowest distortions which were 10 to 14 percent. Distortion levels for configurations 2 and 3 were significantly higher than the values achieved with configuration 1. These configurations were evidently unable to achieve radial pressure profiles as flat as those of configuration 1. Subsequent data will show that this was a result of vortices persisting to the compressor face for only configurations 2 and 3. These configurations were designed to have a greater range of effectiveness. Because of these wake patterns at the compressor face and the limited number of total pressure takes, it is possible that higher distortions existed for configurations 2 and 3 than those recorded. Thus, the superiority of configuration 1 over the other configurations in reducing distortion was at least as great and possibly somewhat greater than indicated in figure 9(a). This superiority disappeared as the model angle of attack was increased to 5° (fig. 9(c)). In fact, at 5° the data indicated configuration 1 to be the least desirable configuration; but lack of knowledge as to the upper limit of distortion for configurations 2 and 3 makes a meaningful comparison difficult.

Vortex-Generator Performance

The compressor face rake profiles of figures 10 and 11 illustrate the ability of the vortex-generator configurations to energize the retarded flow region for varying degrees of supercritical operation. In figure 10, the spike is at its design position; and in figure 11, it is extended. The supercritical values quoted in figures 10 and 11 were defined as the drop in total pressure recovery from the critical value computed as a percentage of the critical value. It is again apparent that the low-recovery, near separated air, normally near the centerbody without generators, was replaced with higher energy air by generator mixing of higher recovery air into the boundary layer thereby preventing formation of the retarded flow region. The improvement in pressure recovery near the duct centerbody was achieved at the expense of the recovery near the outer duct wall. The maximum recovery without generators occurred at about the second pressure probe from the outer wall. This peak was lowered by vortex-generator action. Thus, the generators appeared to promote mixing over the entire stream. At critical design conditions (fig. 10(a)), the peak value was decreased and the radial rake profiles became flatter. At supercritical conditions (figs. 10(d) and 11(d)), the entire profiles were switched from low hub pressure to high hub pressure profiles.

The ability of the vortex generators to energize the centerbody region was dependent on the particular flow field at the generator station. At critical design conditions, the generators were operating downstream of the inlet normal shock. Because this shock had a theoretical static pressure rise ratio sufficient to induce flow separation (ref. 12), the generators were probably operating in a near-separated flow similar to that shown by the rake total pressure profiles of the clean configuration. As illustrated in figure 10(a) by the increase in pressures near the centerbody, the generators could perform well in this environment.

A more severe flow environment was at critical operation with an extended spike position, which caused the shocks from the cowl to fall aft of the centerbody turn. As figure 11(a) shows, the recovery near the duct hub without vortex generators was much lower at the off-design position than at design (fig. 10(a)). Despite this, the use of generators still improved the recovery near the inner-duct wall although somewhat less than at design. Still lower recoveries near the centerbody were obtained with the inlet at critical conditions and 5° angle of attack as illustrated in figure 12. Without generators, the lowest recoveries at 5° were near the inner-duct wall in the lower half of the duct. Vortex generators improved recoveries in this region but simultaneously reduced the recovery near the top of the duct. The generators were thus apparently capable of some circumferential flow redistribution from top to bottom as a consequence of their ability to prevent flow separation.

At the more supercritical inlet operating conditions, the vortex generators were situated forward of the normal shock. From inlet longitudinal static pressure distributions such as those of figure 13, it was estimated that the terminal shock train passed aft of the vortex-generator station at about the first supercritical point (figs. 10(b) and 11(b)). As the inlet was operated at further supercritical conditions, the vortex generators were immersed in a supersonic flow field at about Mach 1.45 and appeared to operate effectively in this environment. They prevented flow separation on the centerbody at terminal shock strengths that caused flow separation on the cowl (see figs. 10(d) and 11(d)). At supercritical operation, the vortex generators were operating ahead of the incipient separation point associated with the terminal shock, presumably in a region of thin boundary layer. Reference 5 noted that optimum-vortex-generator performance in subsonic flow was realized only if the generators were placed far enough upstream of the point of incipient flow separation. Supercritical inlet operation, although placing the generators in a supersonic flow field, satisfied these requirements better than did critical inlet operation.

Vortex Dissipation

The vortices produced by vortex generators have been experimentally observed to dissipate. This dissipation is an important factor in applying them to diffusers because of conflicting requirements: the vortices should persist for a sufficient distance to provide uniform diffuser discharge profiles; but if they persis too strongly at the compressor face, they may cause excessive flow turbulence and induce compressor stall. Reference 5 traced vortices aft of an equally spaced, counter-rotating system of vortex generators and determined a downstream location at which the vortices were greatly dissipated. The vortex dissipation or wake disappearance seems to be related to the theoretical lift-off of the vortices from the surface. The vortices resulting from counter-rotating systems of vortex generators can be considered in pairs. Aft of diverging generator pairs, the vortices induce high-energy air toward the surface. These vortices tend to repel each other. Aft of converging generator pairs, the vortices induce low-energy air from the surface outward into the main stream. These vortex pairs attract each other. The lift-off of the vortices occurs at a downstream station where the vortices inducing flow away from the surface approach each other very closely. Theoretically, this reinforcement of the flow from the surface also transports the vortices away from the surface (ref. 10). Reference 5 observed that the vortices were greatly dissipated at this station.

In terms of the generator spacing parameter of the current test, the vortices of reference 5 dissipated eight pair spacings S downstream of the generators. Using the spacing S of configuration 1 (fig. 8), the compressor face rakes were computed to be 10.3 S aft of the generators. Thus, data from the rakes would not be expected to show evidence of vortices. Discrete vortex patterns could be expected for configurations 2 and 3, however, as the rake station for these configurations were only 6.8 S and 5.1 S, respectively, from the generators. These expectations were consistent with the theoretical trends in range of effectiveness of each configuration as discussed earlier.

Configurations 1 and 1A were compared for possible evidence of discrete vortices (fig. 14). With configuration 1, the compressor face rakes were directly aft of converging pairs of vortex generators. Conversely, the rakes were aft of diverging generator pairs when configuration 1A was used. If vortices existed at the rake station, the diverging pairs of configuration 1A would produce a higher pressure recovery aft of the generators than the lower recovery expected with the converging pairs of configuration 1. The rake profiles for both configurations (fig. 14) were quite similar indicating little evidence of strong vortex action. Some remnant of vortex action may have occurred at critical (fig. 14(a)) as evidenced by the slightly higher pressure of configuration 1A over configuration 1 near the duct center. However, no consistent pressure differences existed at supercritical conditions (fig. 14(b)). The configurations 1 and 1A were also compared at critical conditions over the Mach number range (fig. 15). No significant difference in pressure recovery, inner-duct relative recovery, or distortion was found. The absence of differences between configurations 1 and 1A thus demonstrated a lack of discrete vortices as anticipated from reference 5.

Evidence of discrete vortices was found in the case of configuration 3. As was shown in figure 8 for configuration 3, the compressor face rakes with circumferential locations of 30°, 150°, and 270° were located aft of converging generator pairs. Alternately, the rakes at 90°, 210°, and 330° were located aft of diverging pairs. Each of these sets of rakes produced different profiles as would be expected for discrete vortices. The rakes at 90°, 210°, and 330° (aft of diverging pairs) recorded higher total pressure recoveries about one-third of the way from the inner-duct wall than the alternate set of rakes. This can be seen by an examination of the second total pressure probe from the inner wall in figures 10 and 11 which revealed an alternating pressure fluctuation from rake to rake around the duct. Where pressures near the inner-duct wall were very low at critical conditions (fig. 11(a)), little rake-to-rake variation was found. At the more supercritical conditions (notably figs. 11(c) and (d)), the change in profile from rake to rake was very evident.

Direct evidence of the expected vortex patterns for configuration 2 was not discernible in the rake data because each radial rake was aft of a similar (diverging) pair of generators. Therefore, each rake would be expected to show a generally similar pattern except for some asymmetrical effects caused by the vertical struts shown in figure 4. Due to their orientation, the rakes aft of configuration 2 should experience higher pressure recoveries than rakes aft of a configuration without discernible vortices. A comparison of the pressures of configurations 1 and 2 near the duct center (fig. 10) seem to support this expectation, but the corresponding pressures of figure 11 do not. Evidently, effects due to configuration differences mask the effects of orientation. Further indication of increased pressure recovery with configuration 2 can be seen in figure 9. The total pressures obtained for configuration 2 were generally somewhat higher than was expected by a comparison to the static pressure levels of the vortex-generator configurations. This was especially evident at Mach number 2.0 and at 5° angle of attack (fig. 9(c)). The total pressures of configuration 2 were higher than those of configurations 1 and 3, whereas the static pressures were not.

Thus, configuration 3, and probably configuration 2, have active vortices persisting to a farther aft location than configuration 1. This is in general agreement with theoretical expectations and the experimental results of reference 5. In the limited range investigated, the dissipation of vortices prior to the rake station, as in the case of configuration 1, did not deteriorate the generator performance.

SUMMARY OF RESULTS

Vortex generators were installed aft of the throat on the centerbody of a Mach 3.0, mixed-compression, axisymmetric inlet. The performances of three configurations of generators were investigated at Mach numbers from 2.0 to 3.0. Configuration 1 consisted of 18 pairs of equally spaced, counter-rotating vortex generators. Configuration 2 was formed from 12 pairs of generators by increasing the spacing between converging pairs by a factor of 2. Configuration 3 consisted of nine pairs of equally spaced generators having twice the spacing of configuration 1. The following results were obtained:

1. All three generator configurations improved the diffuser performance about equally as shown by increased total and static pressures at the diffuser exit.
2. Distortion was reduced by all vortex-generator configurations, with configuration 1 having the lowest distortion at 0° angle of attack.
3. The effectiveness of the vortex-generator configurations in reducing distortion and increasing diffuser performance was undiminished at angles of attack to 5°.
4. All configurations were equally capable of energizing the normally retarded flow region near the centerbody.
5. With the inlet operating at supercritical conditions, the vortex generators were forward of the normal shock in supersonic flow where they continued to function properly.
6. Evidence of discrete vortices persisting aft from the generators to the compressor face was observed for configurations 2 and 3 only, in agreement with theoretical and experimental expectations.
7. Configuration 1 performed as well as the other configurations and successfully dissipated the discrete vortex structures at the compressor face.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 15, 1968,
720-03-01-62-22.

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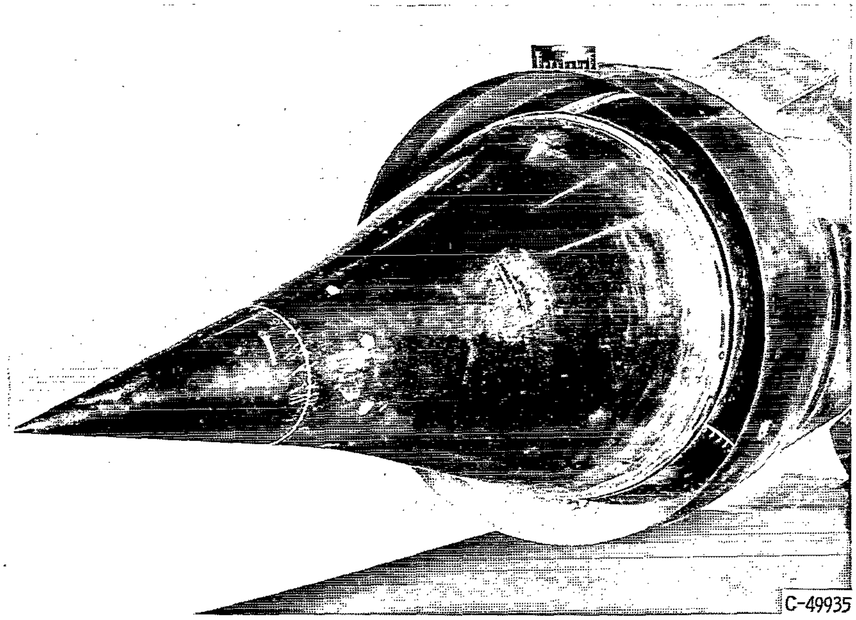


Figure 1. - Mach 3.0 mixed compression inlet.

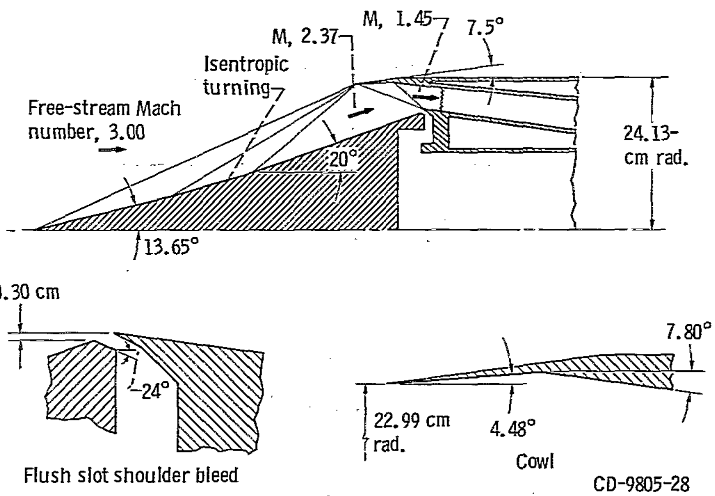


Figure 2. - Design of axisymmetric, mixed compression, Mach 3.0 inlet.

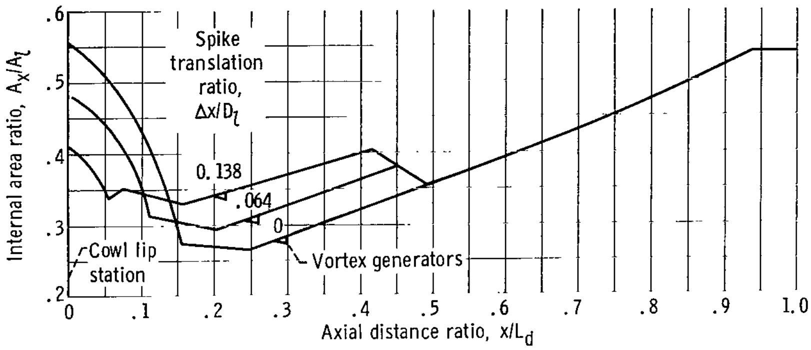


Figure 3. - Variation of diffuser internal area ratio for various spike positions. Subsonic diffuser length, 73.66 centimeters.

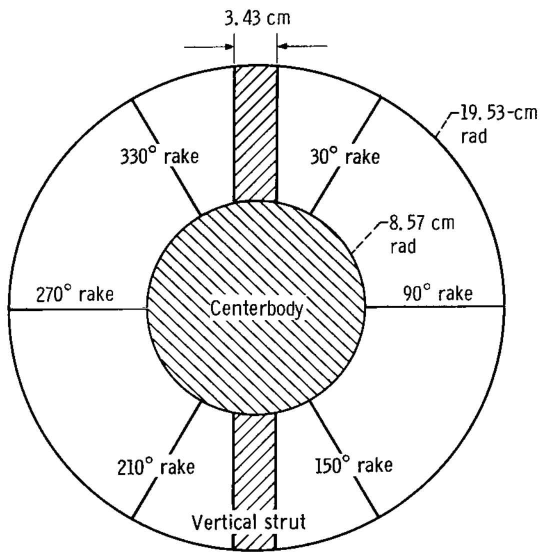


Figure 4. - Simulated compressor face station.

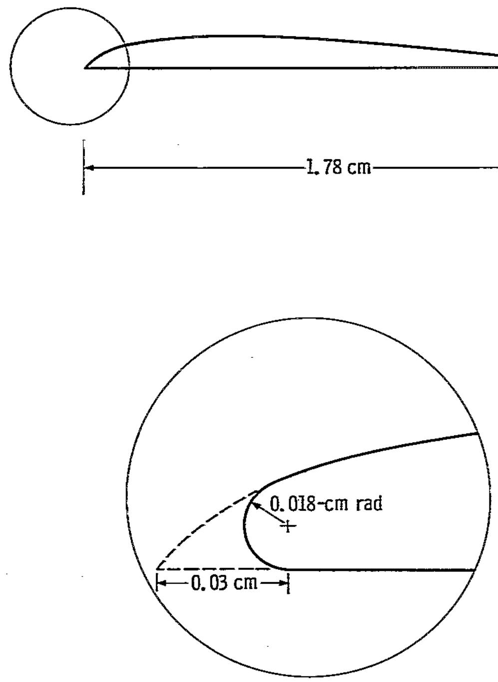
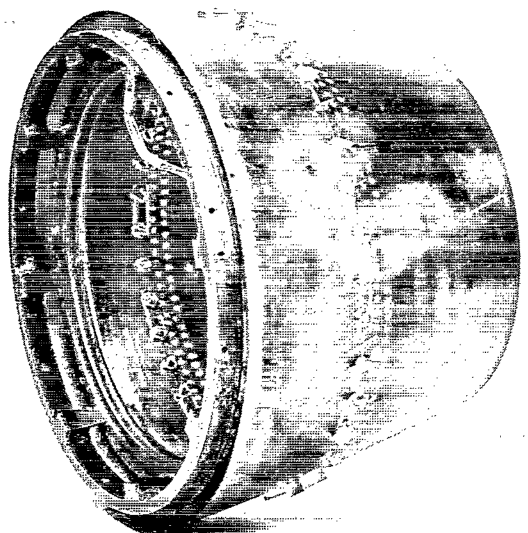


Figure 5. - Vortex generator detail.

Figure 6. - Vortex generator installation on model centerbody.



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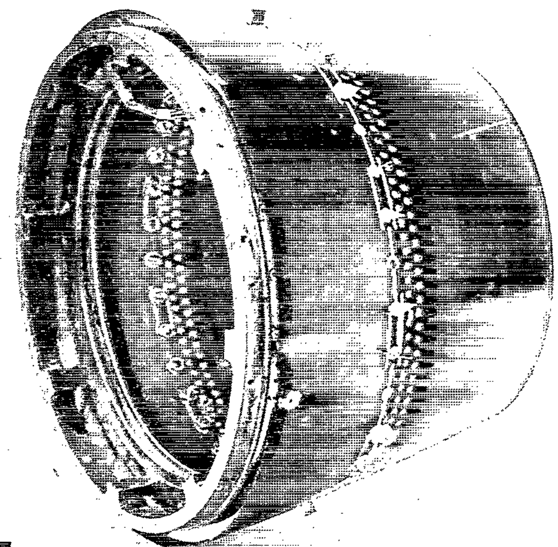
(a) Configuration 1.



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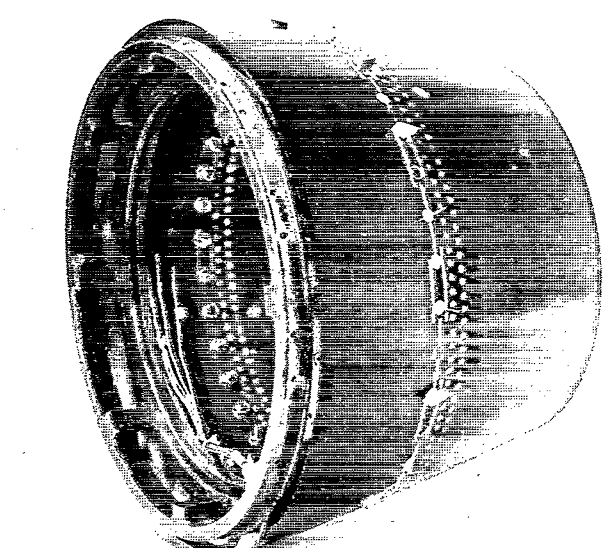
(b) Configuration 2.



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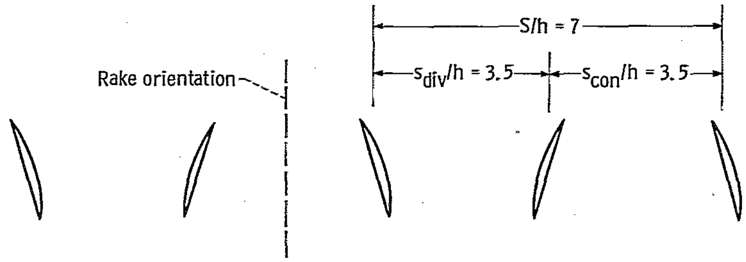
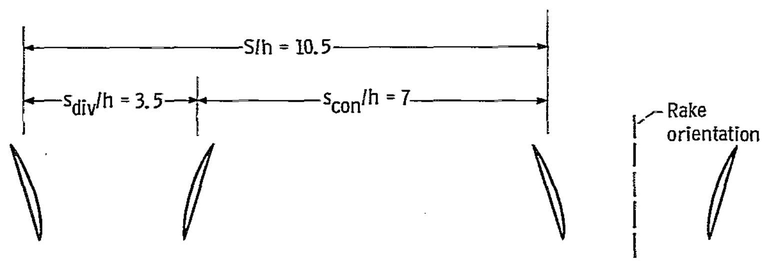
(c) Configuration 3.

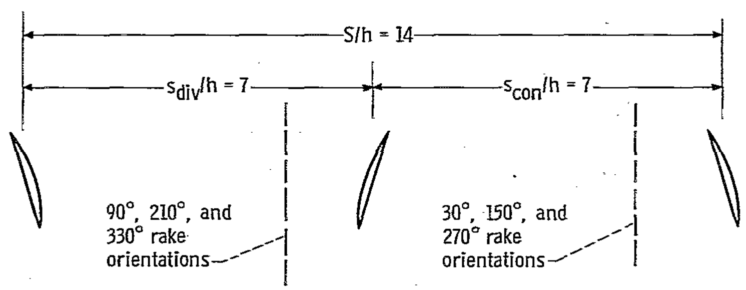
Figure 7. - Installation of vortex generator configurations.



(a) Configuration 1; S/s_{div} = 2.

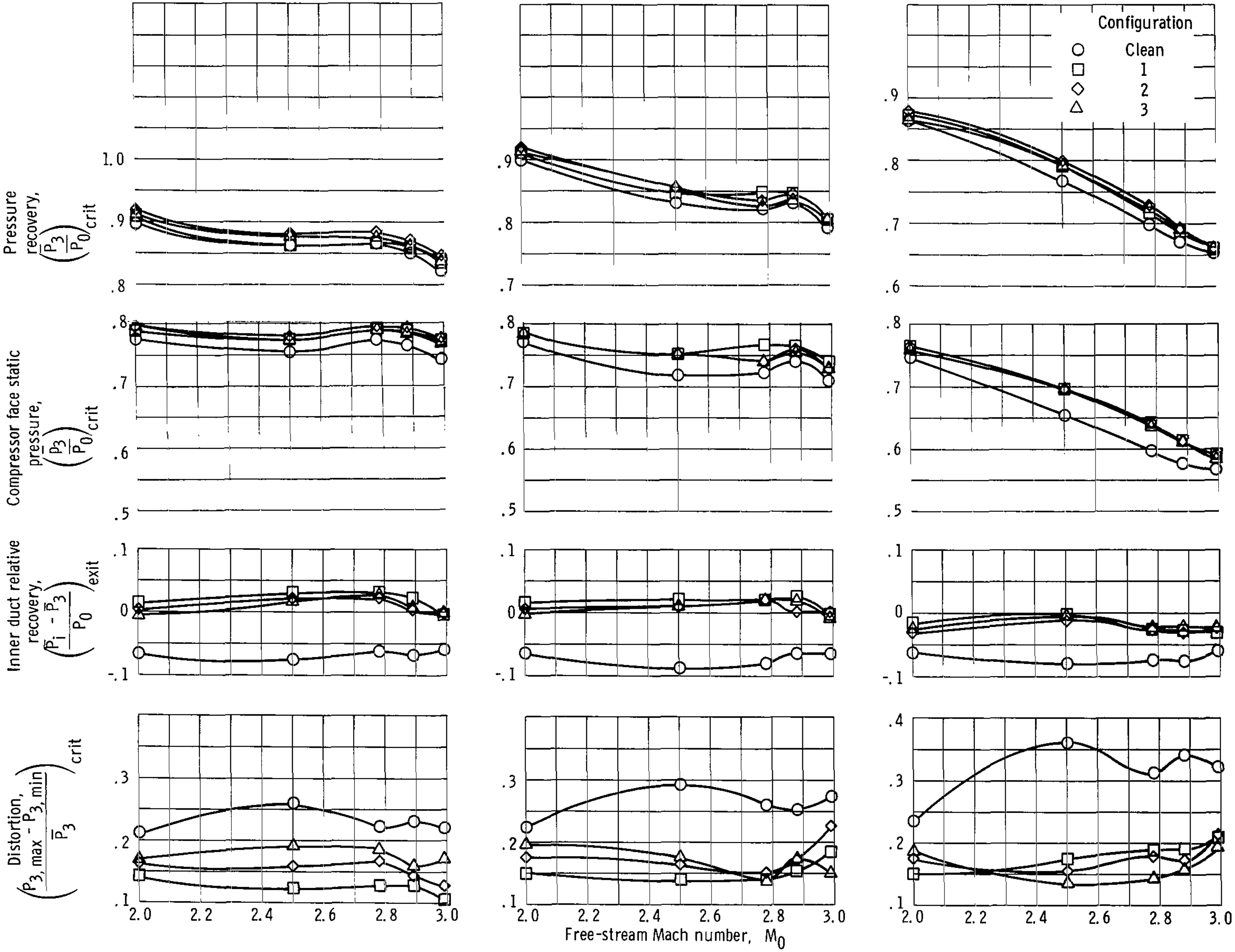


(b) Configuration 2; S/s_{div} = 3.



(c) Configuration 3; S/s_{div} = 2.

Figure 8. - Vortex generator configurations.

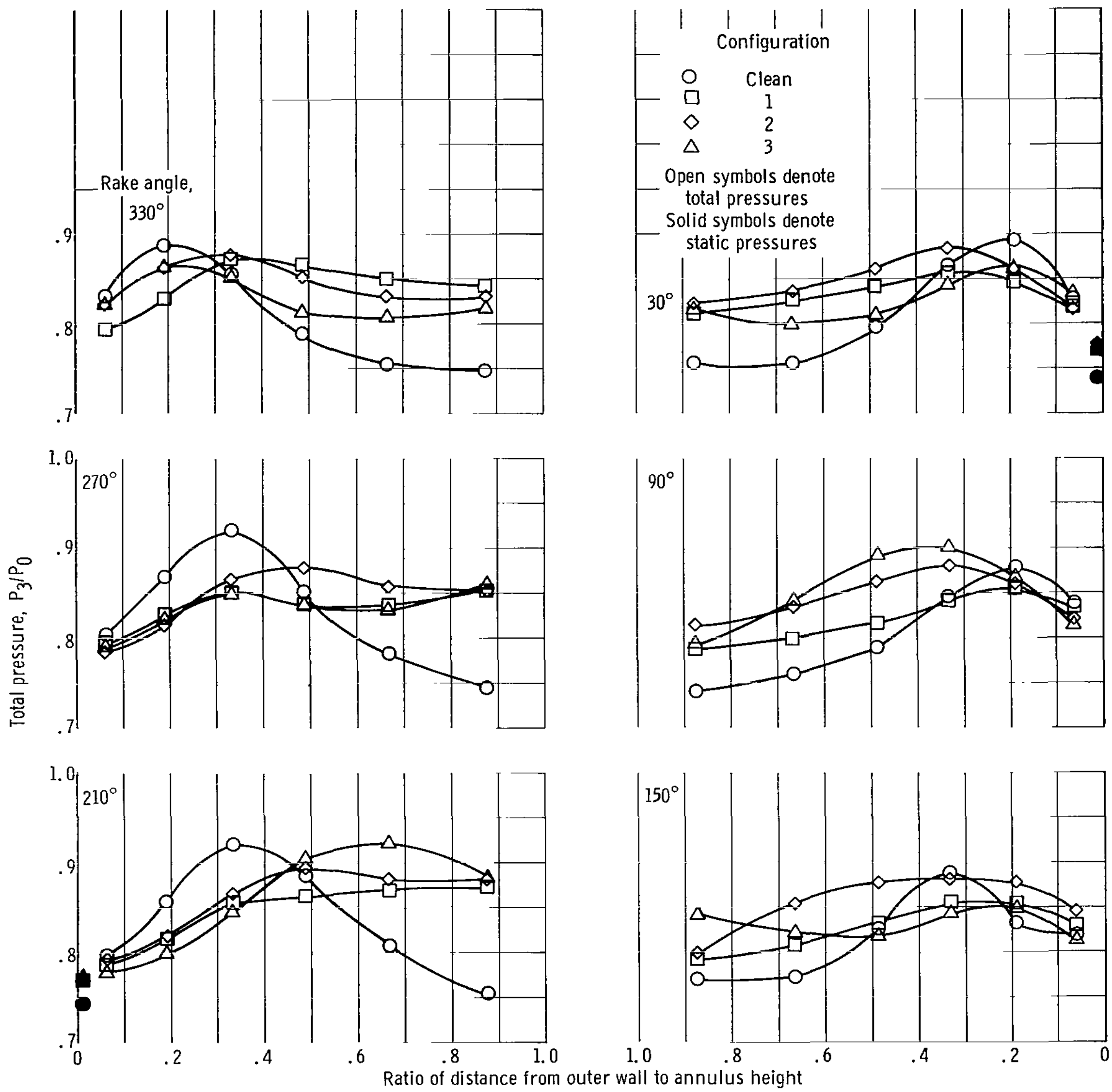


(a) Angle of attack, 0.

(b) Angle of attack, 2°.

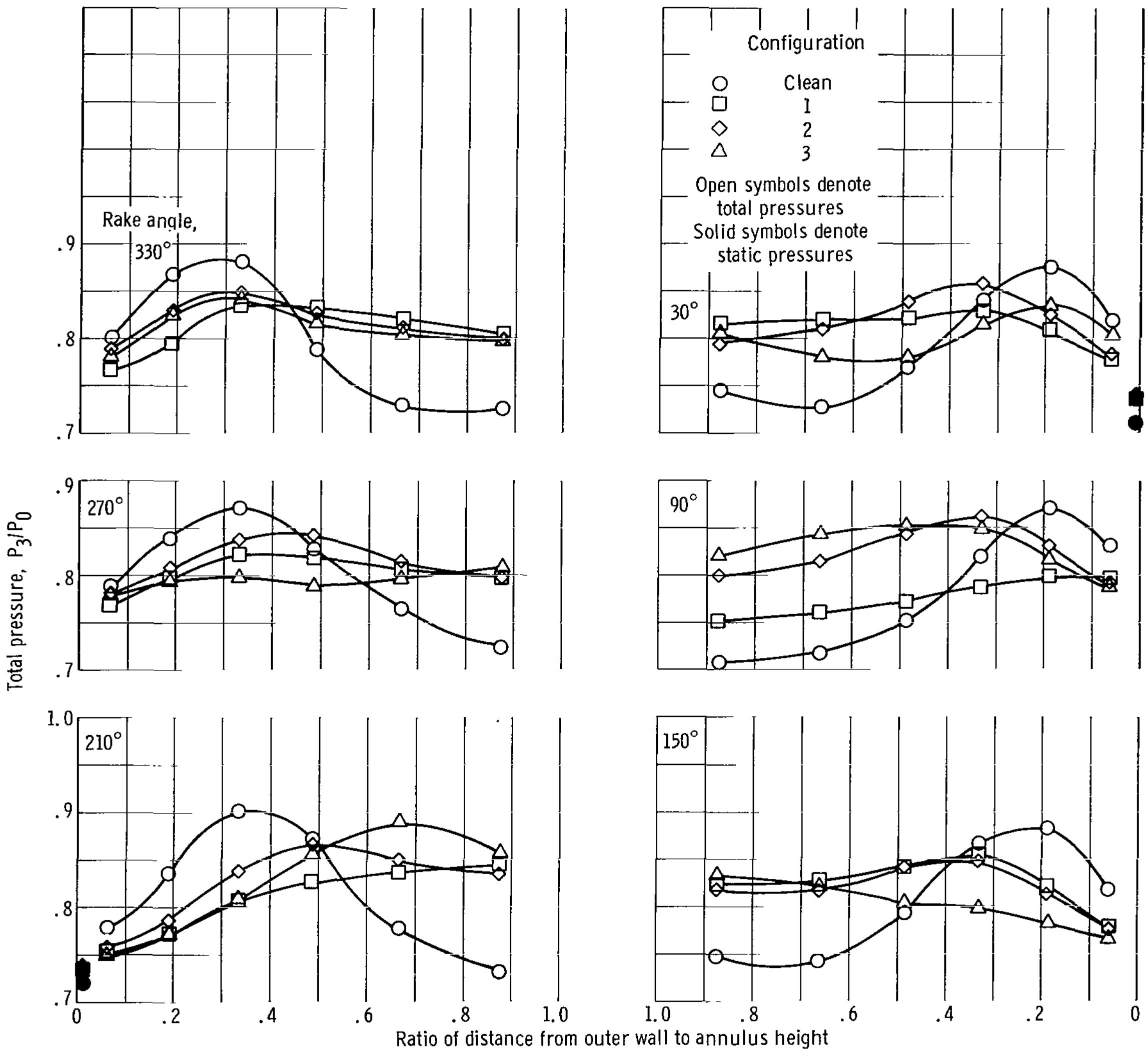
(c) Angle of attack, 5°.

Figure 9. - Effect of vortex generators on critical performance.



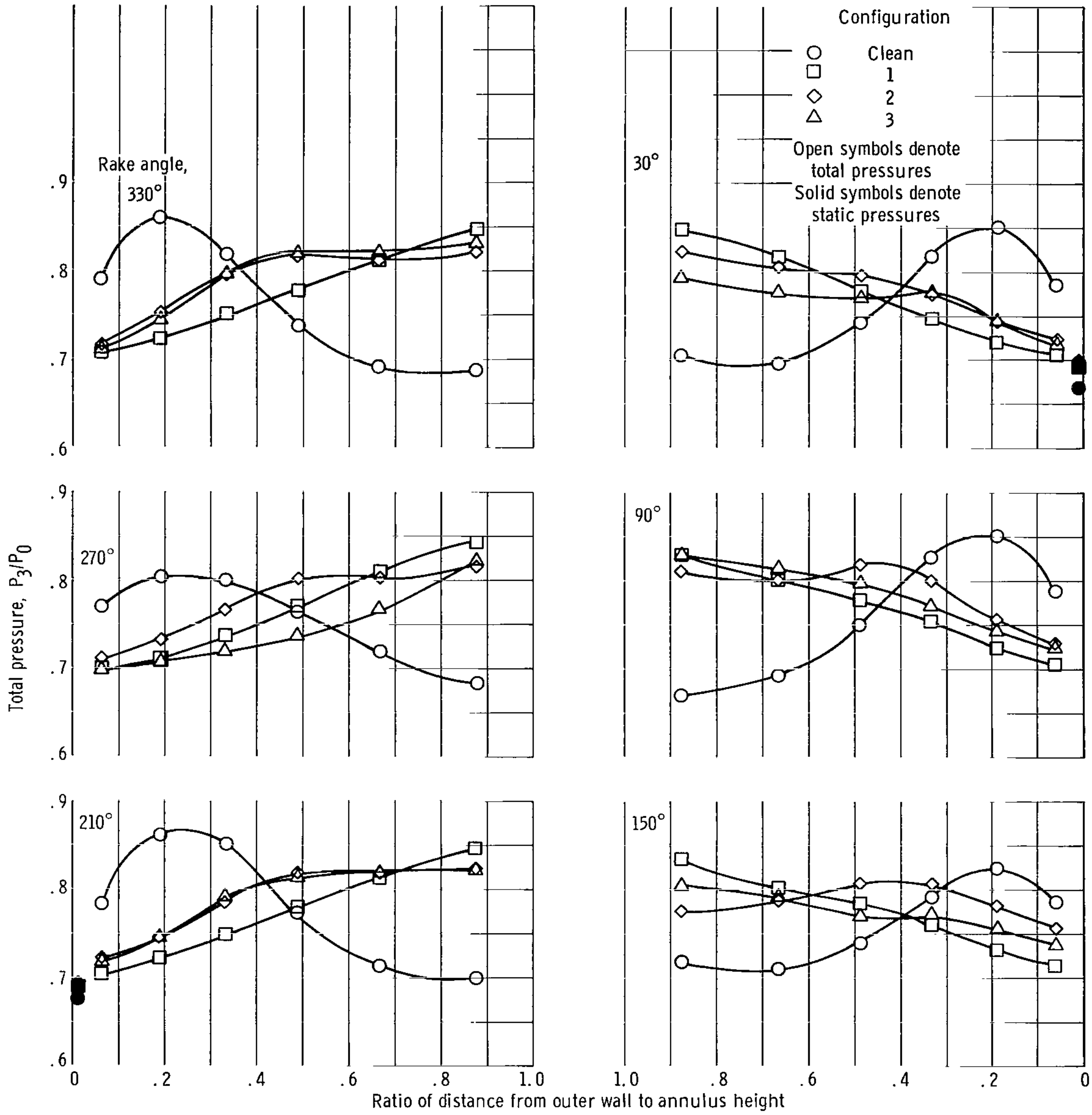
(a) Critical operation.

Figure 10. - Effect of vortex generators on compressor face rake profiles at design conditions.



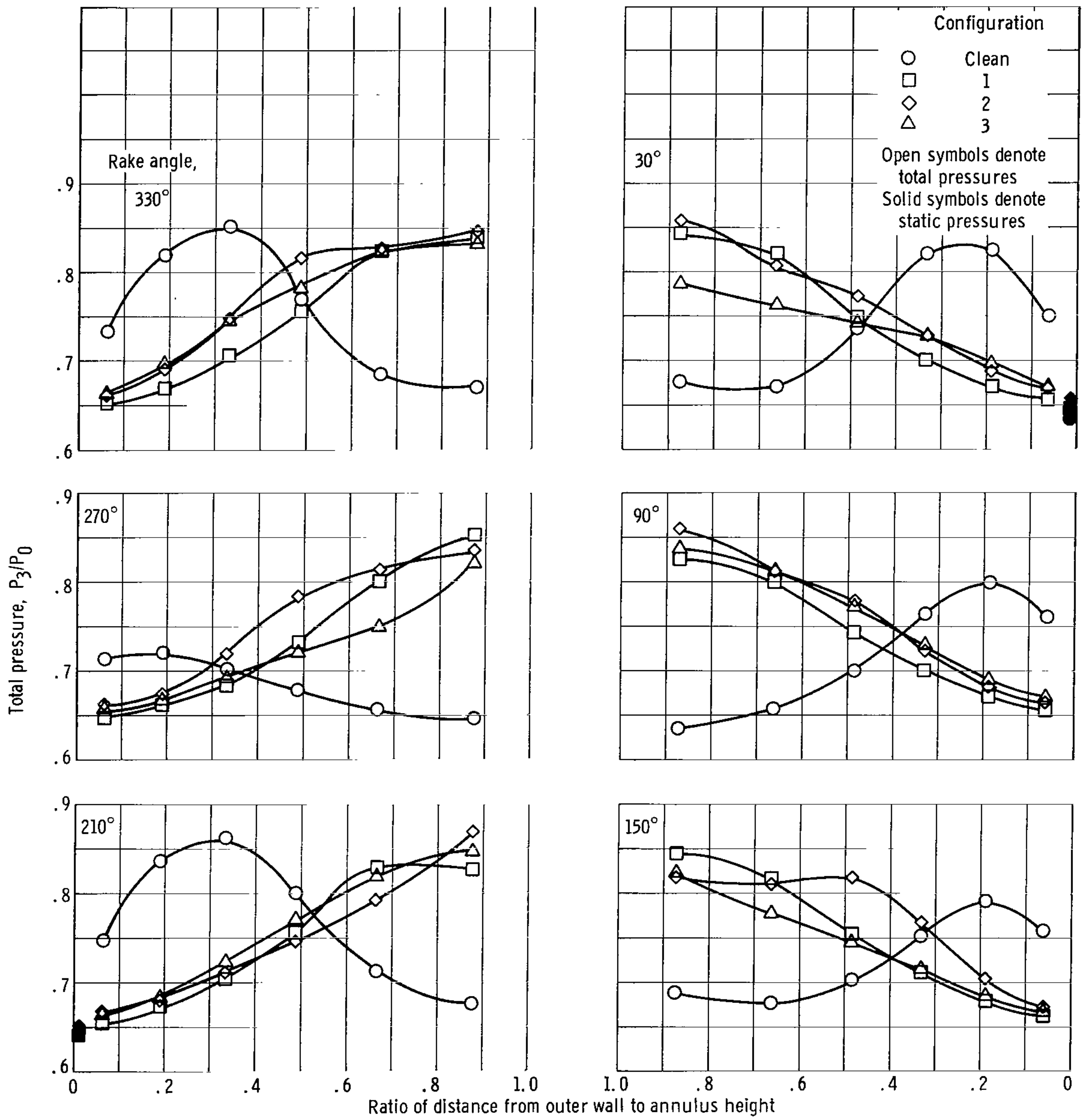
(b) 3.5-percent supercritical operation.

Figure 10. - Continued.



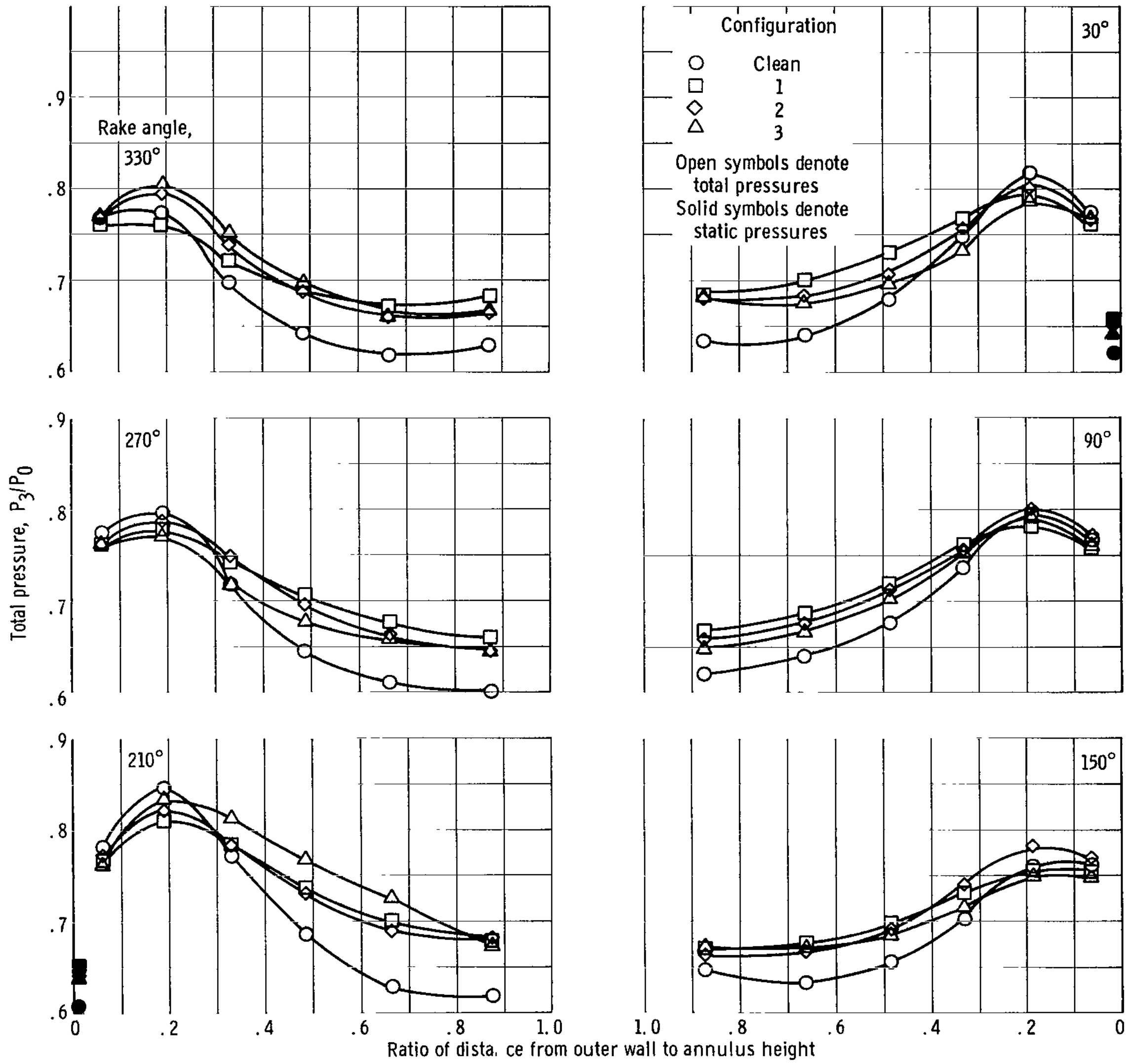
(c) 8-percent supercritical operation.

Figure 10. - Continued.



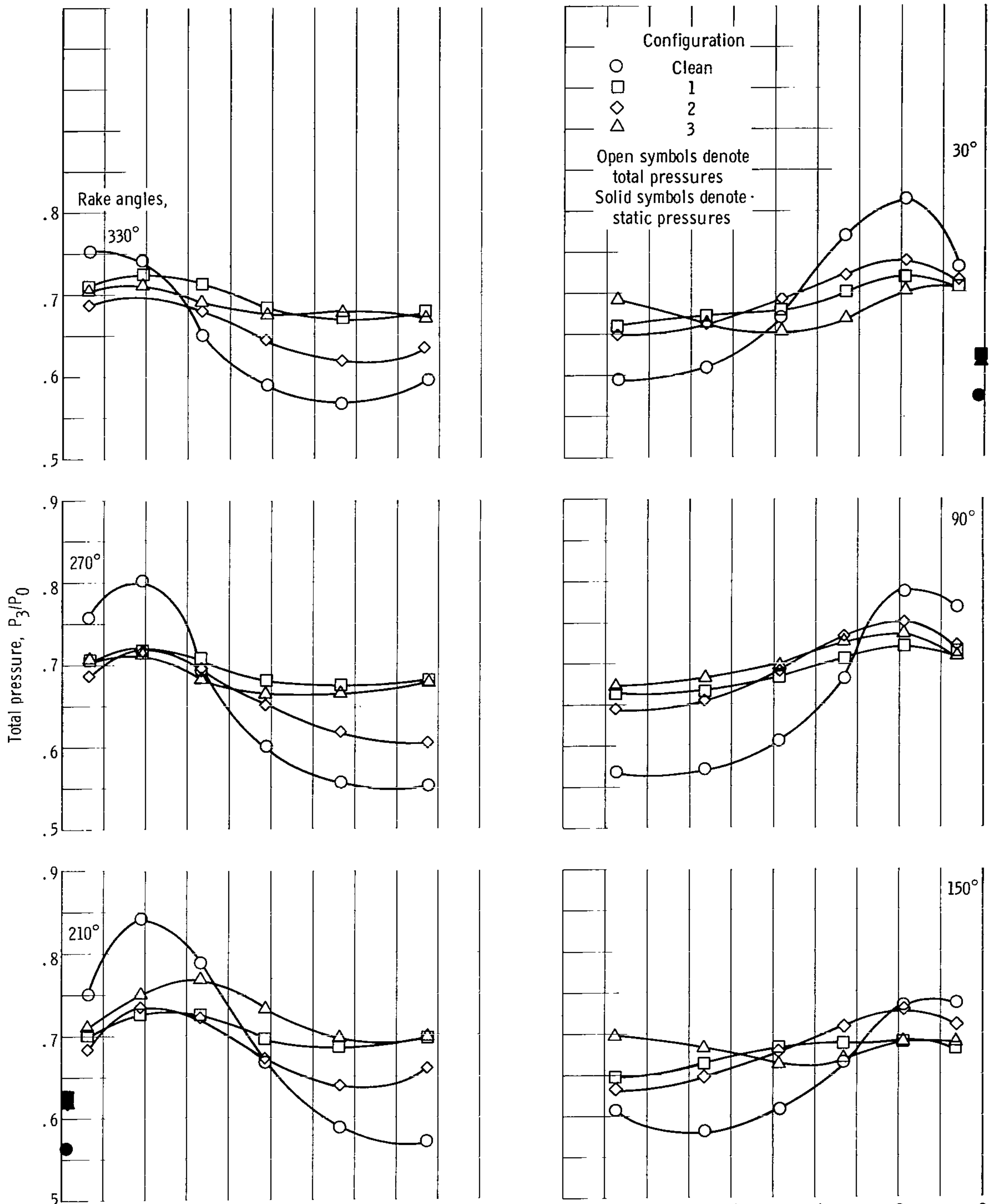
(d) 11.5-percent supercritical operation.

Figure 10. - Concluded.



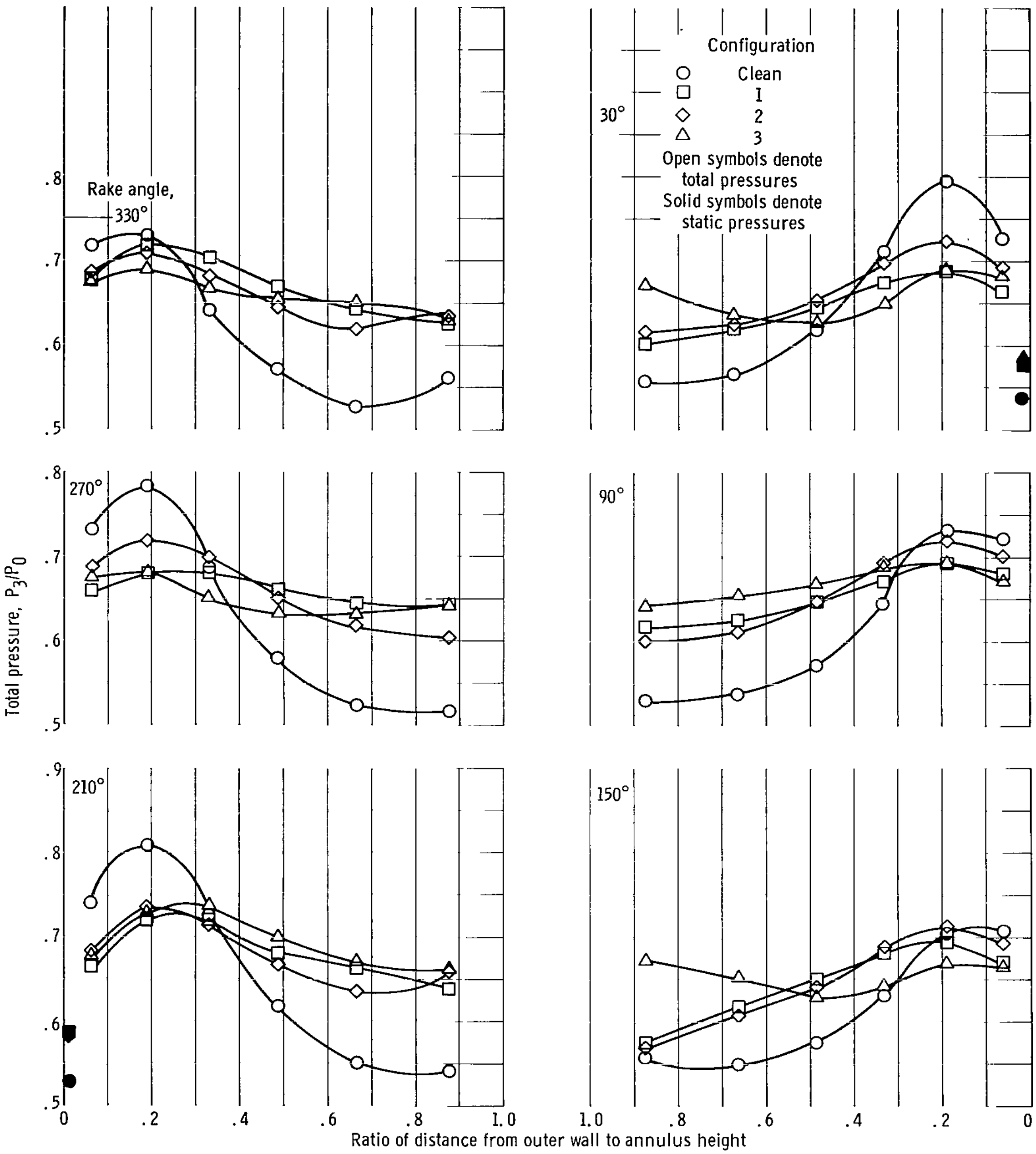
(a) Critical operation.

Figure 11. - Effect of vortex generators on compressor face rake profiles with spike extended. Spike translation ratio, 0.041; Mach number, 2.99; angle of attack, 0°.



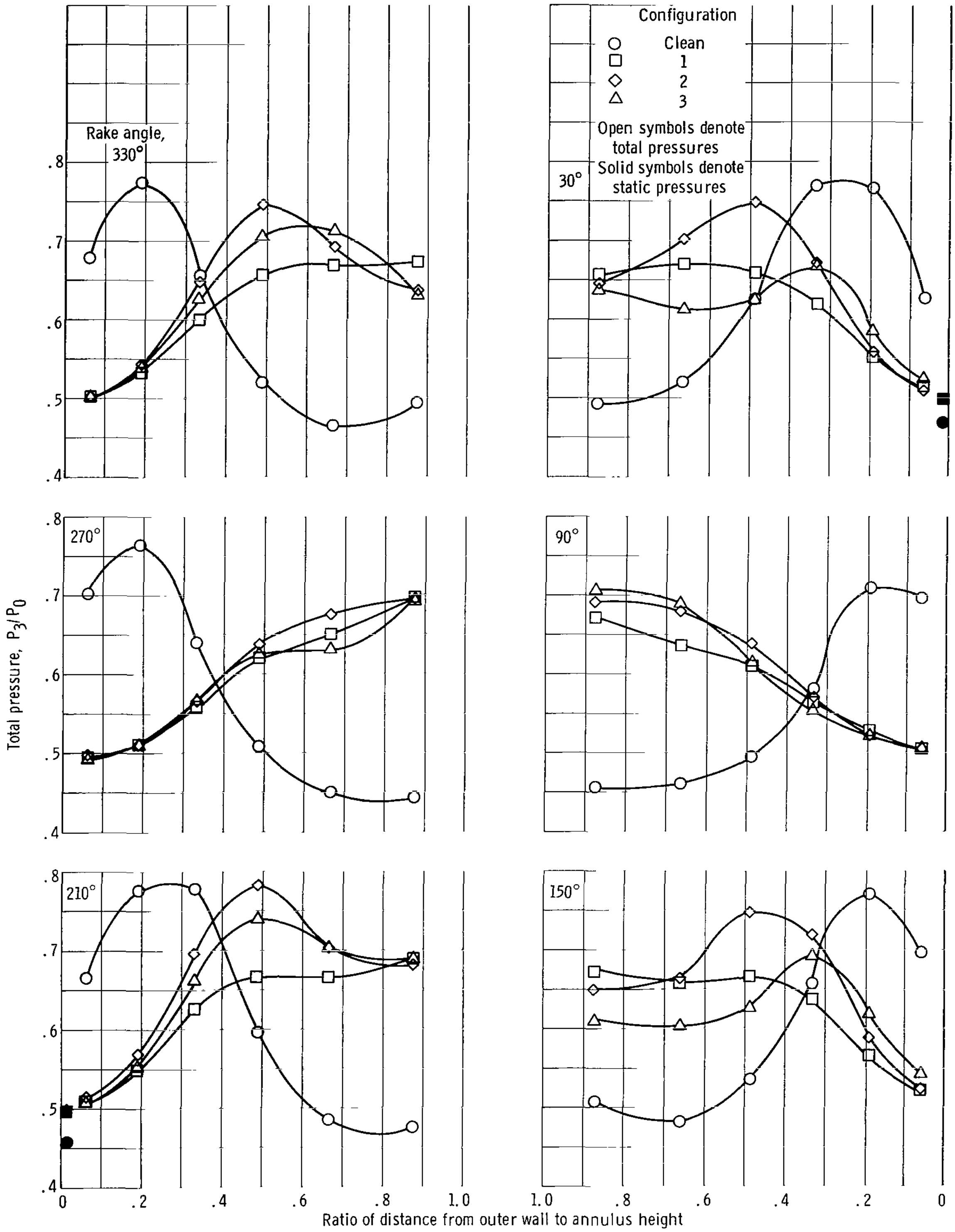
(b) 4-percent supercritical operation.

Figure 11. - Continued.



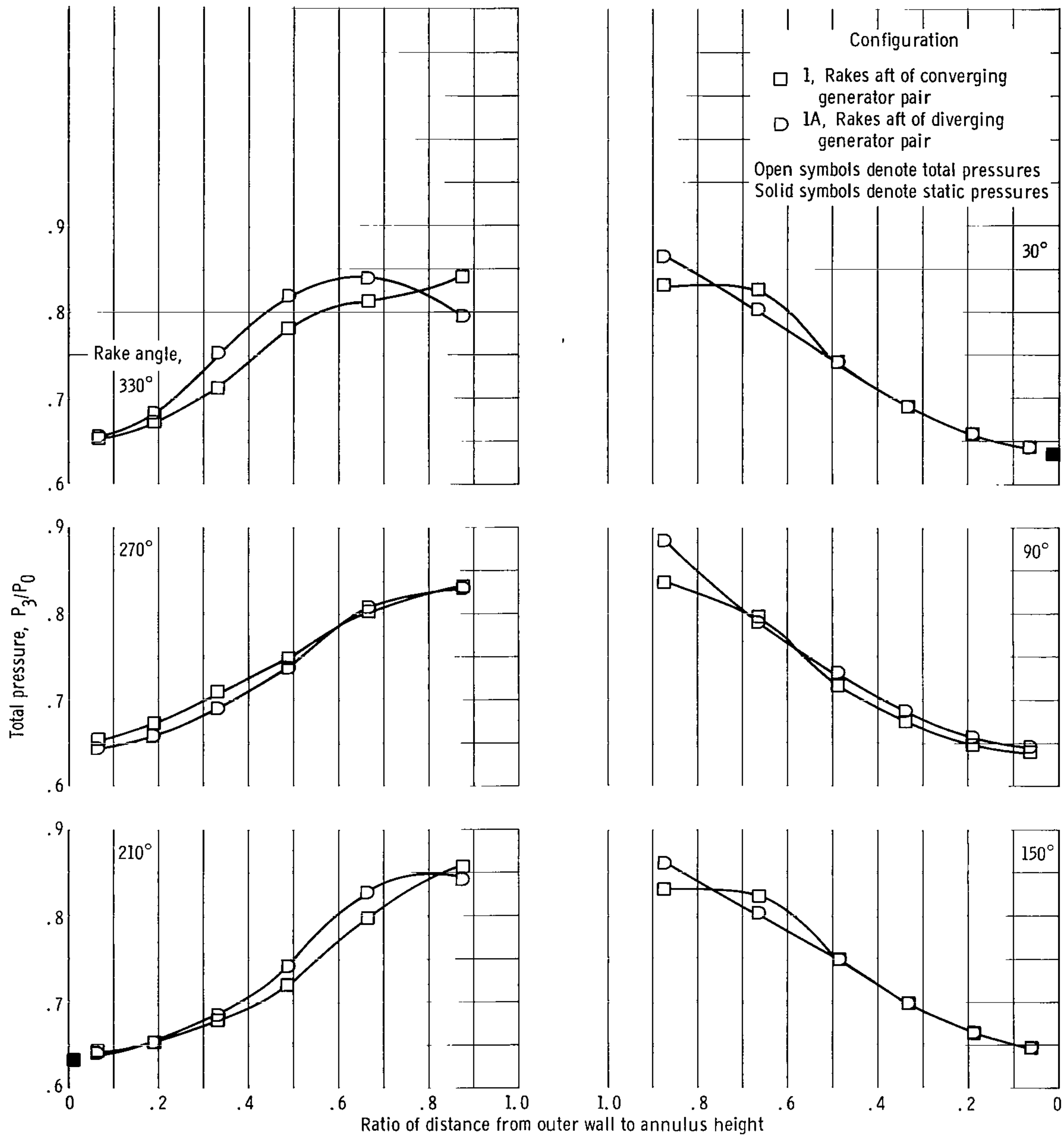
(c) 8.5-percent supercritical operation.

Figure 11. - Continued.



(d) 15-percent supercritical operation.

Figure 11. - Concluded.



(b) 13-percent supercritical operation.

Figure 14. - Concluded.

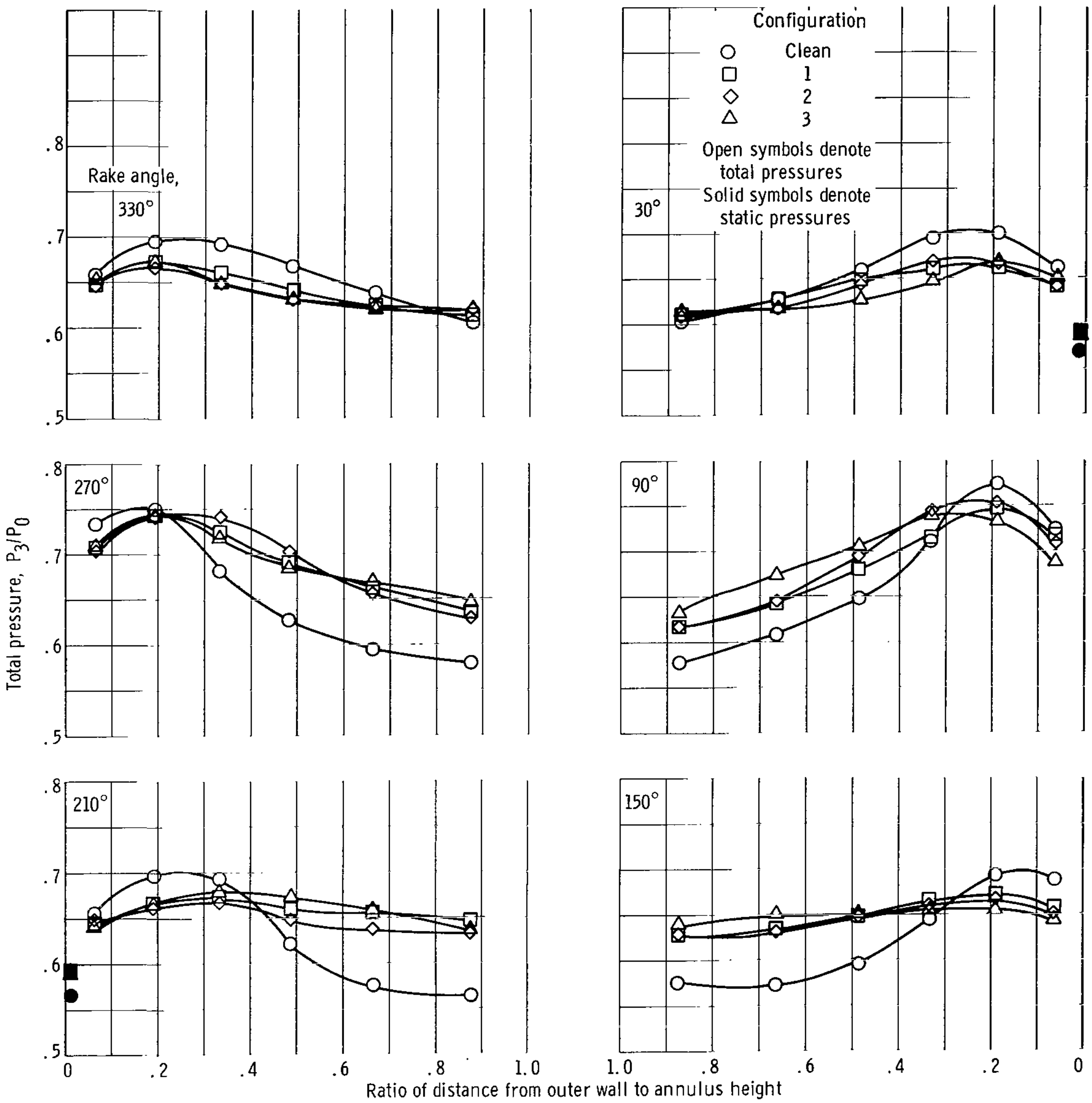


Figure 12. - Effect of vortex generators on compressor face rake profiles. Mach number, 2.99; angle of attack, 5°; spike translation ratio, 0.051; critical operation.

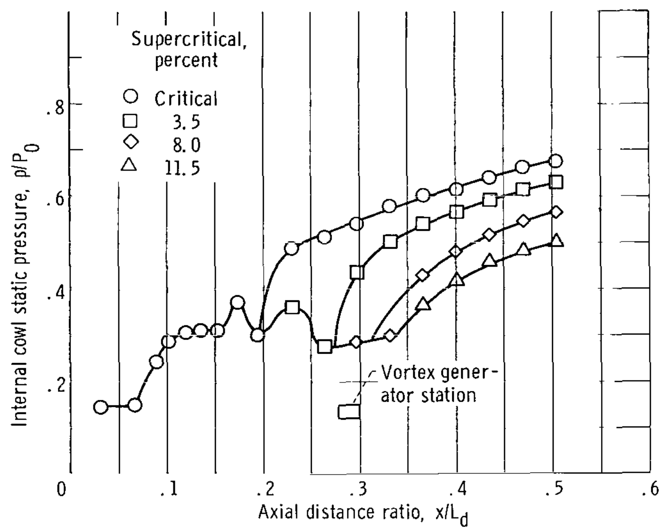
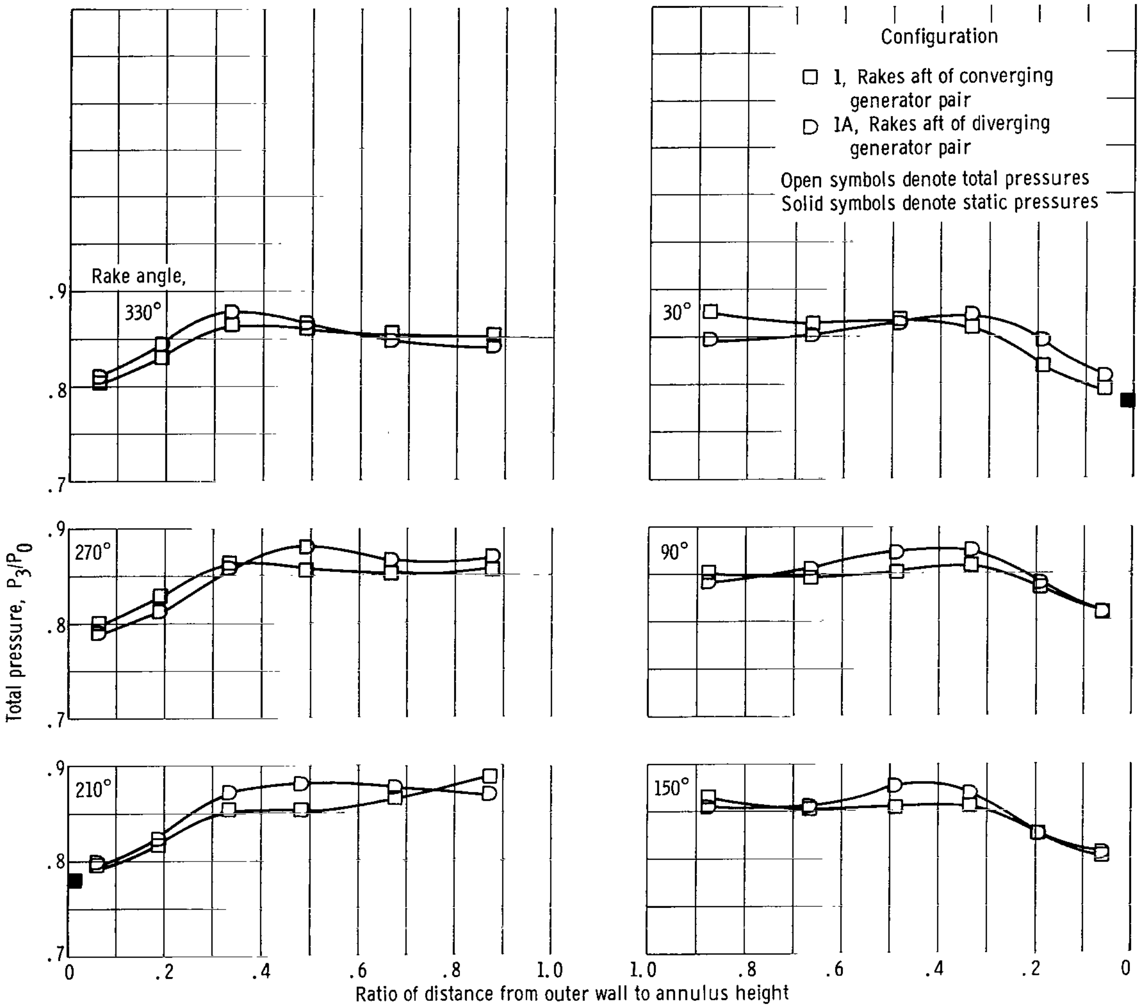


Figure 13. - Internal cowl pressure distributions at design spike position. Mach number 2.99.



(a) Critical operation.

Figure 14. - Effect of generator to rake orientation on compressor face rake profiles. Mach number, 2.99; angle of attack, 0°; spike translation ratio, -0.002.

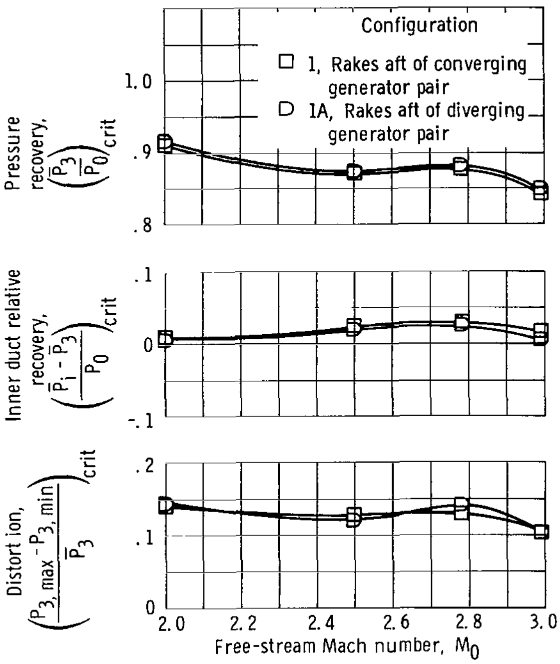


Figure 15. - Effect of generator to rake orientation on critical inlet performance.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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